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DEPLOYER: A ROBOT-DEPLOYING ROBOT

by
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14. ABSTRACT
This report documents a program to develop techniques for launching and controlling heterogeneous teams of robots. The key goal is to combine the physical and computational power of a large, sophisticated robot (the Deployer) with the robustness and flexibility of a swarm of distributed microrobots. Under this program, iRobot developed proof-of-concept systems for two objectives. The first objective is the ability to strategically emplace microbots and microsensors. A high mobility platform (the iRobot Urban Robot) is equipped to launch grenade-sized robot mock-ups through1st, 2nd, and 3rd story windows in urban terrain. The second objective is the ability to command and control the robots once emplaced. This task includes coordinating among the beterogeneous robots to extend the capability of each type, providing the operator with distributed remote presence at a minimized cognitive load, and intelligently collecting, filtering, and presenting a coherent view of the data.

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Preface

This report outlines the research undertaken by iRobot Corp. (formerly IS Robotics, Inc.), Somerville, MA, to develop techniques for launching and controlling heterogeneous teams of robots. The key goal is to combine the physical and computational power of a large, sophisticated robot (the Deployer) with the robustness and flexibility of a swarm of distributed micro robots. The project was completed during the period December 1999 to June 2001 under contract number C-DAAD16-00-C-9219, under the direction of the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, Natick, MA, and the sponsorship of the Defense Advanced Research Projects Agency (DARPA).

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1 Summary

The Deployer program develops techniques for deploying and controlling heterogeneous teams of robots. The goal of the Deployer program is to combine the physical and computational power of a large, sophisticated robot (the Deployer) with the robustness and flexibility of a swarm of micro robots.

A multirobot team is able to solve problems that would be impossible to solve with a single large robot or an unsupervised group of simple robots. As an example, a highly mobile ground vehicle designed for urban terrain can climb a flight of stairs and then deploy small mobile sensors to explore a different floor of a building. Alternately, the vehicle could launch small, unattended air vehicles over the battlefield for a bird's eye view, or mobile detractors (for example robots bearing smoke, noise makers, etc.) through windows of multistory buildings prior to breach. By learning how to control groups of robots with diverse capabilities, one can extend the capabilities of multirobot teams to solve a wide variety of problems for both military and civilian applications.

Consider the following scenario: an unmanned vehicle (the Deployer) enters an unexplored area. Its mission may be to find people in a burning building, neutralize nuclear, biological, or chemical contaminants, locate terrorists, or identify unexploded ordnance. The Deployer releases a swarm of smaller robots (microbots). The microbots spread out through the building, moving down hallways and into other rooms. As the microbots carry on their search of the area, the Deployer acts as their supervisor. The Deployer does not micromanage the microbots' movements, but instead monitors their progress, collects data from the swarm, builds maps, and directs the swarm toward unexplored areas. When the microbots find an item of interest (such as a human victim), the Deployer can navigate through the swarm and deliver a payload (for example, medical supplies).

Within the context of the Distributed Robotics program, we undertook to study and develop proof-of concept demonstrations of two key areas in multirobot deployment:

1. **Launch**: transport and strategically emplace the microbots to support mission goals.
2. **Command and Control**
    - **Maintenance**: maintain the infrastructure to support the distributed front, including communications, error detection and recovery.
    - **Cooperation:** coordinate to extend the capabilities of each robot type.
    - **Operator Control:** provide a pipeline between the human operator, Deployer and swarm such that the operator can occupy a safe, remote presence with minimized cognitive load.
    - **Recovery**: intelligently collect, filter, and relay distributed data.

For each area, the Deployer robots were the highly mobile Urban Robots developed under the DARPA Tactical Mobile Robotic program. Each Deployer was augmented with special-purpose hardware for the purpose of this study.

Researchers investigated a number of launch methods and built a prototype launcher that launches grenade-sized rounds into 1-,2-, and 3- story windows with enough force to break glass. The designs were based on potential integration with the University of Minnesota Scout robot. The launcher mounts on a Deployer robot.

For command and control, the swarm robots were based on those developed for the sister DARPA program, Software for Distributed Robotics (SDR). IRobot Corp. designed, developed and built a system in which a Deployer robot controls multiple swarm robots under spatially oriented infrared and radio frequency communications. An operator interface allows the user to command and control both the Deployer and the Swarm (individually or collectively), and to view data collected from the Swarm via the Deployer.

The program advanced the state of the art in autonomous and semi-autonomous control of multirobot teams, including:

- **Coordinated motion**
    - Deployer leads the Swarm
    - Swarmbots make way for the Deployer
- **Topological/metric mapping**
    - Deployer determines Swarmbot locations and uses this data to build a map containing topological and metric information.
- **Topological navigation**
    - Deployer plans and executes paths using the Swarmbots as beacons
- **Coordinated search**
    - Deployer and Swarm cooperate to search an unknown area
- **Grid-based mapping**
    - Swarmbots explore and the Deployer builds an occupancy grid map
- **Visually-guided motion**
    - Deployer uses vision to guide Swarmbots to specified location

In addition, we developed a **unified map** display that can superimpose the maps constructed by the Deployer/Swarm on an existing floor plan. The operator can use this tool to register local grid maps with the global grid map.

2 Introduction

2.1 Background

There is a concerted effort at DARPA and in the research community to develop very small robots. Because of their small size and potentially low cost, micro and miniature robots can be carried and deployed by individuals and small teams to augment human capability, perform hazardous missions, or perform missions presently unimaginable. These robots may be distributed throughout a building, along a protected perimeter, or within a hostile or hazardous environment. The DARPA Microsystems Technology Office (MTO) Distributed Robotics sponsors the development of such robots at a small (less than 5mm square) size. The robots employ revolutionary design approaches such as the ability to reconfigure, the ability to work as a system, and biologically inspired locomotion.

One drawback to the program is that *people* deploy the robots. As a result, either the person must enter a potentially hazardous area or the robot must travel from a distant deployment site to the target area, before ever performing its designated task. The former solution is unsafe and the latter sacrifices size and cost to satisfy unrelated power, durability, and mobility requirements. What is needed is *another robot* to deploy the micro robots.

A second drawback is that, by virtue of their size, the microbots have limited sensing, on-board intelligence and communications. The presence of a single more-powerful and versatile robot among a swarm of distributed micro robots would have a significant impact. For example, a smarter robot could recognize key features, such as doorways, and direct the insensate swarm toward them.

A third disadvantage to fully distributed swarms of small robots is the requisite load on the soldier commanding the swarm. By centralizing control through the more powerful robot, the operator need maintain only a single link to the entire swarm. That link can take advantage of long-range communication and high fidelity sensing (e.g., video, audio, etc.). The Deployer robot becomes the remote presence within the swarm for the operator. Moreover, the Deployer can acquire and assimilate data from the swarm and present it to the operator in a coherent framework.

2.2 Deployer: a robot-deploying robot

The Deployer program is to develop a system that pools the capabilities of small penetrating robots and a rugged deployment robot. The complete system allows for an in-depth study of issues involved in robots controlling robots, including:

- Launch and emplacement
- Activating and controlling deployment,
- Operator control, and

- Intelligently collecting, filtering, and relaying data.

This report is intended for review by the sponsoring members of DARPA and the Soldier Systems Center.

3 Methods, Assumptions and Procedures

3.1 Study Objectives

A number of preliminary requirements meetings were held with DARPA management, other contractors within the Distributed Robotics (DR) program, and user representatives at Soldier Systems Center.

The initial DARPA objectives were to focus on novel launch capabilities for one or more of the micro robots being developed under the DR program. Two designs were recommended for further consideration: the Xerox Parc "PolyBot" and the University of Minnesota "Scout."

The PolyBot, a reconfigurable set of blocks that could form various shapes, was an extremely interesting choice in that it could effectively add manipulator arms to the Deployer robot. However, its development timeline stretched far beyond the duration of this program. The current prototypes were very fragile, were tethered and demanded significant power draw. As such, they could not be launched in any compelling way.

The Scout was more mature and, in concept, designed for launching. Redesign was required to adequately ruggedize the robots for a power launch and a communications protocol was needed between Scout and Deployer. The U. Minnesota chose not to support either effort, due to intellectual property (IP) concerns.

Nonetheless, the Scout was a viable candidate for future integration and iRobot determined to investigate launch mechanisms for Scouts, using dummy slugs in place of actual robots for experimentation and validation.

Impetus for a second direction for the program - - to control the distributed robots once they were on the ground - - gained momentum in meetings with Soldier Systems Center user representatives. They noted that launching concepts were high risk and of moderate value. Command control of a deployed swarm, on the other hand, was deemed very important. Together, iRobot and the Army developed a first response scenario for emergency technicians. In this scenario, the Deployer directs a small swarm of robots to first invade a room and then disperse to gather information, such as human presence or temperature readings. The data is passed backed to the Deployer who relays it to a human operator in order to provide critical preliminary information before emergency personnel enter the room. The Deployer calls back the swarm and proceeds to the next room to repeat the process. The development of a system that would perform key aspects of such a scenario became a program objective.

In sum, two complementary study objectives became apparent. One, to investigate launching mechanisms for a Scout-like robot, and two, to consider command and control (C^2) operations once the robots are on the ground. In the context of the Distributed Robotics program and the development of a Deployment vehicle (the Deployer), the two objectives may be broken out as follows.

1. **Launch**: transport and strategically emplace the microbots to support mission goals.
2. **Command and Control**
    - **Maintenance**: maintaining the infrastructure to support the distributed front, including communications, error detection and recovery.
    - **Cooperation:** coordinating among heterogeneous robots to extend the capabilities of each type.
    - **Operator Control:** providing a pipeline between Operator, Deployer and Swarm, so that the operator can occupy a safe, remote presence with minimized cognitive load.
    - **Recovery**: intelligently collecting, filtering, and relaying data.

The Deployer and the microbots share the capabilities to perform each phase. The goal of this project was to best define where specific capabilities should rest and how to best integrate them, given current or near-term technologies.

An ancillary objective was to leverage previous and concurrent DARPA work to every extent possible.

3.2 Study Approach

1. Launching Mechanisms – the approach is to prototype one or two novel methods of launching "Scout-like" vehicles off of an Urban Robot, a rugged platform developed under the DARPA Tactical Mobile Robotics (TMR) program. Five concept ideas are outlined below (Section 3.3): a sudden simultaneous scatter launch of robots and distracters (noisemakers, smoke); a controlled glider; and three directed launches (compressed spring, catapult, and ballista). Each has direct application to military and law enforcement missions. One design would be selected to be developed into a working prototype with dummy robots.

2. Command and Control – the approach is to develop algorithms that leverage the heterogeneous interaction between a "smart" deployment robot and a team of deployed, distributed robots called "Joeys" (*i.e.*, the term used to describe the children of marsupials).

The deployment robot will be an augmented Urban Robot. The Deployer's "smarts" are due to better sensors, better communication, connection to a human operator, and a better viewpoint (*i.e.*, sensors, antennae are higher off the ground), as compared to the Joey.

The swarm of Joeys will be a combination of commercial off-the-shelf (COTS) RugWarriors™, acquired under the Software for Distributed Robotics program (SDR) and prototype platforms developed in-house. The Joey design will focus less on form-factor (a thrust of the DR program) and more on the identification of key algorithms for heterogeneous missions. The Joeys will leverage work done for the SDR program, concentrating this effort on the interaction with the deployment vehicle.

3.3 Launching Concepts

A number of launch concepts were considered. These fall into 3 general categories:

1. Simultaneous Disbursement Launch
2. "Mount" Observation Scenario (overview observation platform)
3. Directed Trajectory Emplacement

The imagined Joeys for all of these launches are in the general Scout size regime (Section 5 Related Work, Current Efforts - University of Minnesota). Outside dimension limits for Joey launch packages are assumed to generally be from a nominal 40 mm Dia. X ~110 mm long cylinder, up to a soft drink can size 64 mm Dia. X 124 mm long cylinder. The Deployer is an iRobot Urban Robot.

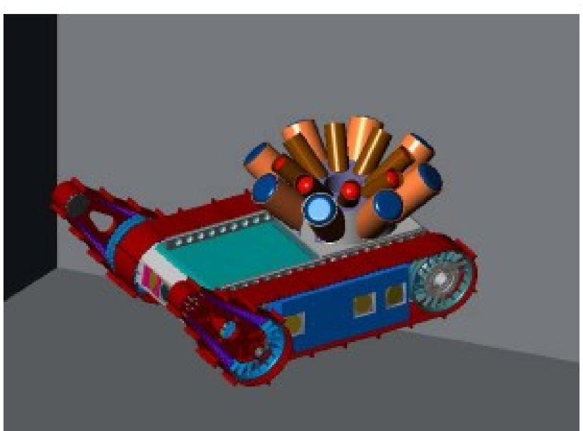
3.3.1 Simultaneous Disbursement Launch

Scatter Launch

Joeys arrayed in a circular cassette magazine could be spun up to launch energy about a vertical spin axis. Pairs of Joeys, up to the full magazine complement, can be released at one instant, thereby producing fast area disbursement. The launch trajectories can be horizontal, which would minimize at least floor impact g's. Or the release could incorporate a ramp, which would loft the Joeys at a selected (e.g., 45^{o}) launch angle to clear obstacles and achieve different placement objectives.

It is also possible to release more than one type of Joey from the same spinning magazine. Initially, miniature diversion or sensor modules could be released from an inner ring of the magazine. Subsequently, the larger Joeys with significant mobility could be launched with different selected specific energy.

The following two solid-model sketches (Fig. 1) illustrate this concept. The first shows the launcher tube arrangement. The second incorporates a circularly symmetric protective shroud.



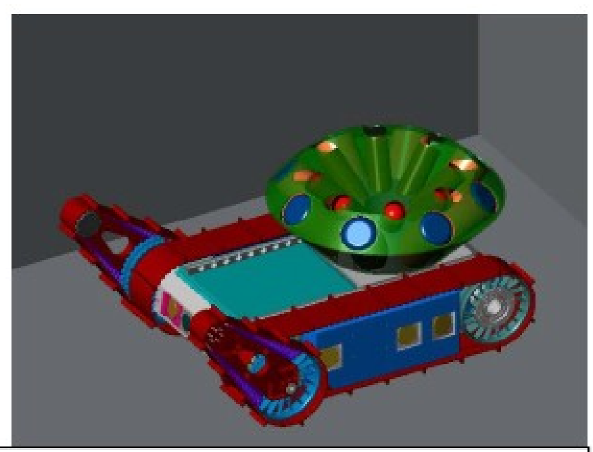


Figure 1: Centrifugal scatter launch

A capability enhancement could also produce directed launches. Angle selected release of a Joey at the necessary kinetic energy would enable directed placement. The main challenge is that launching a single Joey would cause an imbalance in the spinning magazine. In some cases it may be useful to simultaneously launch oppositely directed robots, but in the general case this would be wasteful. It would be less wasteful to release a sacrificial weight, or perhaps a diversionary package, at the same instant to maintain balance. Another design variation could utilize a floating spin center, such as used to accommodate an out-of-balance washing machine drum.

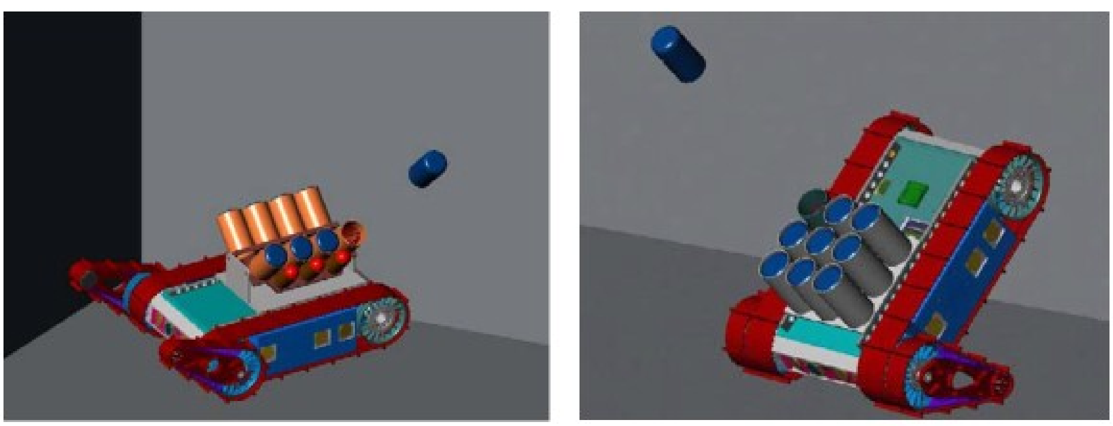
Advantages include: dramatic impact simultaneous launches, moderate complexity, versatility, variable launch energy, and range beyond 50 feet.

Difficulties include: spin-up/down times from 2 to 10 seconds depending upon throw distance, limited placement accuracy.

3.3.2 Directed Trajectory Emplacement

Spring In A Cup

An alternate (and simpler) solution to the scatter launch would be to arrange spring-cup launchers in a circle, for immediate launch but with less energy. The “Spring in a Cup” (Fig. 2) concept uses a compressed spring in a launcher tube, one launcher tube for each Joey. Each launcher tube spring is intrinsically cocked and latched during Joey loading into its launcher. These launcher tubes are arrayed in a group on top of the Deployer.



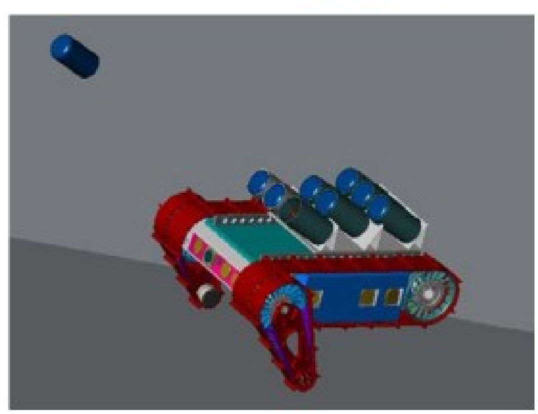


Figure 2: "Spring in a Cup" launch configurations.

Pointing of the arrays can be accomplished in several ways. One uses the Urban flippers to elevate Urban and aim an array of launchers. Typically the launcher tubes would be mounted on the rear half of the robot deck facing forward with a nominal 30° upward elevation angle. Rotating the flippers down could elevate the robot tubes another 30° upward so that the launch could be up to 60° elevation. Six to nine launchers could be mounted in this fashion.

A variation on this fixed launcher tube configuration could utilize an array, which is directed to the sides. Spinning the robot would allow fast deployment of multiple robots. One disadvantage of this configuration is that it would not be possible to utilize the Urban's ability to elevate itself to vary the launch elevation angle.

Another launcher pointing concept would connect 3 to 4 launchers into a rigid group which could be articulated parallel to either the Urban's pitch axis or roll axis. The launcher groups could be laid down during transport, such as in a PackBot bay, and erected to launch attitude for Joey deployment. Two to four groups of 3 or 4 launchers could be supported atop the Urban robot deck in this manner.

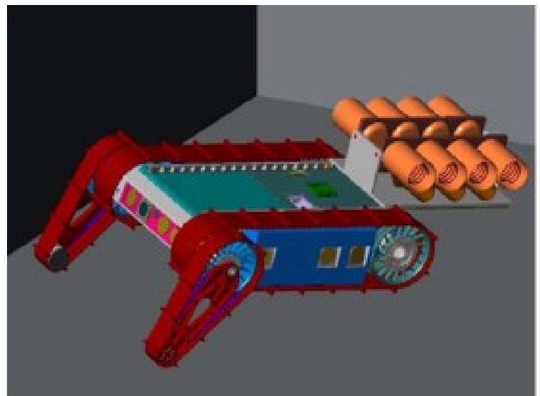


Figure 3: Detachable Launcher.

The launcher pod could be made to be detachable (Fig. 3) from the robot and thereby leave the Urban unencumbered for subsequent Deployer support operations.

Advantages include: launcher and loading simplicity, intrinsic pod detachment option, simple Joey unbiblical attachment / detachment.

Difficulties include: preset fixed launch energy, range limited to less than 25 feet with mechanical springs, (cartridge blanks could be used to substantially increase range, if permitted)

Catapult

The catapult concept being developed utilizes a gear motor cocked spring, with a "cam" governed force (jerk and acceleration) profile. The magnitude of the lofting impulse is controlled by the amount of spring cocking pretension. The release point angle is governed by the elevation of the Urban robot produced with the flippers. This concept has both direction and velocity trajectory control.

The individual Joey robots are arrayed in a magazine to the side of the centrally located catapult, and sequentially loaded onto the launch cradle / clamp.

Advantages include: controllable trajectory, pre-selectable release spin, Joey orientation and spin stabilization which tends to keep the Joey axis horizontal and reduce tumbling, moderately long as well as short trajectories, flat or arched trajectories.

Difficulties include: maintaining and separating Joey umbilical connections, Joey launch and release attachment to the catapult cradle.

Ballistic Launch

A 40mm grenade launcher can be mounted atop the Deployer to feed a Joey a round from a magazine. A nail-gun cartridge, or similar, can be used to power the launch. An ejection mechanism would permit detachment of the launcher, thereby re-enabling the Deployer with its full mobility.

Advantages include: comparatively high launch velocities. The long travel distance of the carriage makes it possible to store more energy, thereby increasing range and making it possible to fire Joey projectiles through windows. A ballista would be more accurate than the short tube spring launchers. Also the mechanism is compatible with standard military equipment.

Disadvantages include: none perceived.

3.3.3 "Mount" Observation

Rocket-Launched ParaCam Glider

A Joey-sized Rocket assembly could contain a packed parafoil wing, RC guidance control, and observation / teleop / observation camera (Fig.4). The rocket would be launched from the Deployer along an elongated rail, or from a directed tube similar to Spring-In-a-Cup configurations. A fixed burn duration would bring the module to sufficient altitude above the observation target. At appropriate altitude and velocity, the rocket assembly would deploy the ParaCam Glider. Alternatives for separation and deployment of the glider include: a “timer explosive" within the rocket motor that would separate / eject the glider from the rocket and protective shell, or alternatively: a passive composite spring member in the leading edge of the parafoil could be coiled within the enclosure and upon release, eject and deploy the glider. Manual teleop would guide the ParaCam over the target using the observation camera and possible operator line of sight observation for guidance.

Figure 4: Concept for the Rocket-Launched ParaCam Glider.

Figure 5 shows a model of a camera, transmitter, RC package, and battery assembly. A propeller and motor are also shown within the package volume illustrating that

propulsion could also be added. The small cylinder below the instrument package is a candidate rocket engine. Other rocket form factors of approximately the same volume are available and would package better and take less vertical height. The transparent cylinder surrounding the assembly represents a soft drink can volume for comparison.

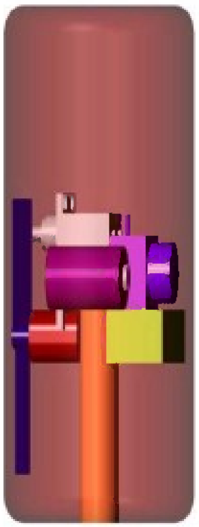


Figure 5: ParaCam Glider components.

Figure 4 shows a representative parafoil model airplane. For a glider configuration, the ParaCam assembly would replace the propulsion package.

There are many other variants of this theme involving rigid airfoils, electric motor driven propeller propulsion, compass orientation, etc. The one described above is the primary candidate.

Advantages include: Mount overview capability, employs reliable, proven, and inexpensive recreational technology, package size compatible with other Joey modules.

Difficulties include: possible teleop control disorientation, limited forward glide speed in windy conditions, parafoil deployment requires some development.

3.4 Launch Prototype

Discussions with the management team concluded that access to multi-story buildings in dense urban terrain was of prime interest. The **Ballistic Launcher** was selected to be prototyped, mounted on the Deployer and tested.

3.5 Command and Control (C²)

In order to perform the heterogeneous command and control missions, iRobot developed supporting hardware and software systems.

3.5.1 C² Hardware Development

Three types of robots were used in this portion of the program. Two Deployer robots were created using Urban Robots as a basis. The Joey robot was designed and built to operate in a swarm. During its production, existing commercial off-the-shelf Swarm robots (RugWarriors™, acquired under the Software for Distributed Robotics program (DARPA IPTO) were used.

ISIS

The ISIS infrared communications system is at the heart of the SDR Swarm project. This system allows individual robots to communicate with nearby robots and determine their range, bearing,

and relative orientation. It also allows the robot to detect nearby obstacles via reflections of its own IR communication packets.

A pheromone message system, using ISIS, provides a means to propagate spatially correlated signals throughout the group. An individual robot can use pheromone messages to determine how many communications hops it is away from the source of the message. Knowing how many communication hops separate two arbitrary robots allows the system designer specify behaviors that are only activated for nearby robots, or far away robots. These messages can also be used to compute global minimums and maximum values of any local quantity.

Deployer Outfitting - Bandicoot

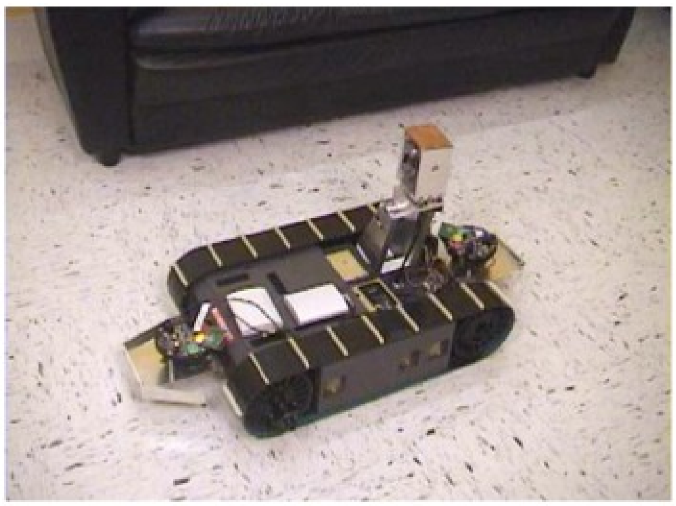


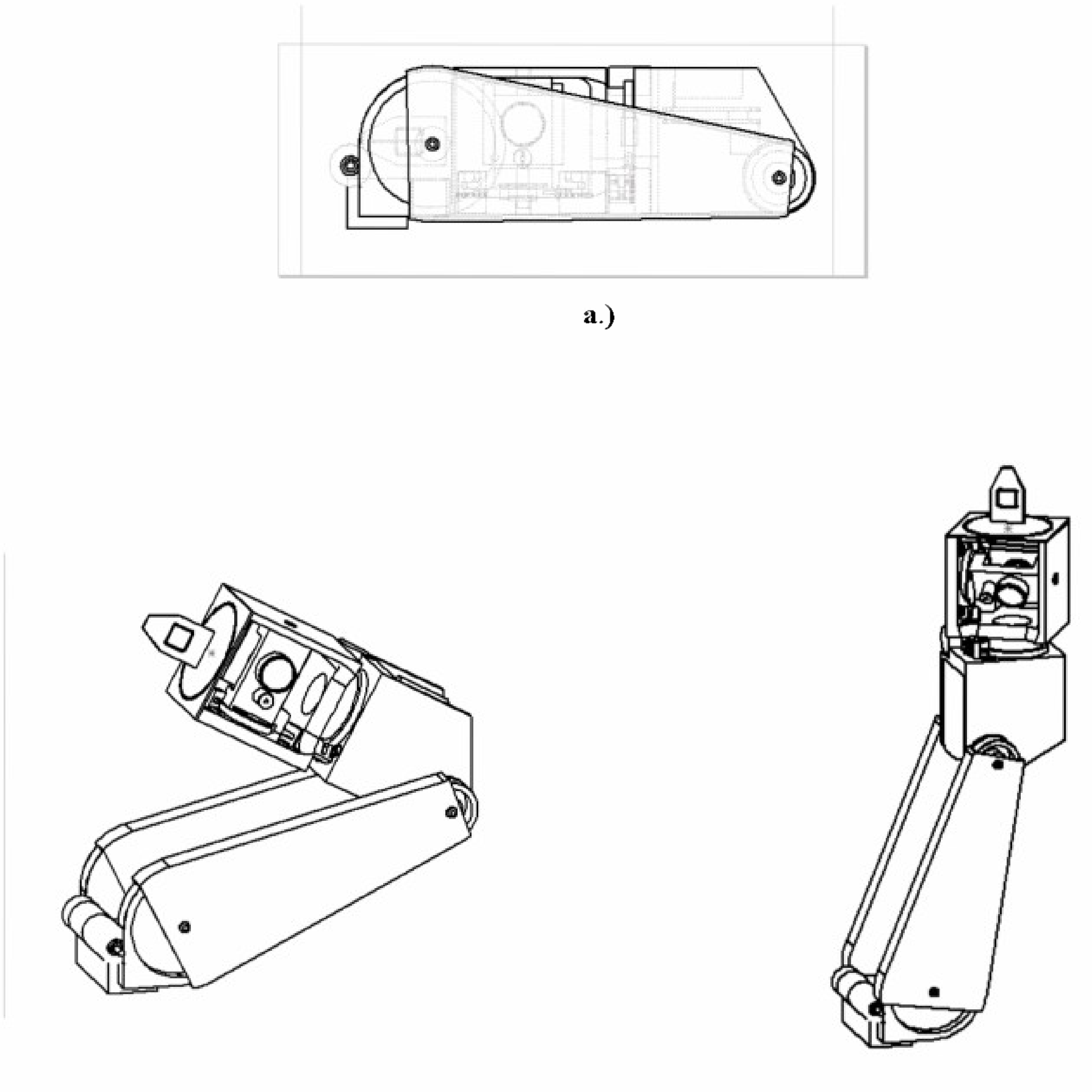
Figure 6: Bandicoot

In keeping with its mission as the command-and-control Deployer, the first Urban Robot, Bandicoot (Fig. 6), was equipped with two Swarm infrared (ISIS) transceivers and a Swarm radio. One ISIS transceiver was mounted on the front of Bandicoot, and one was mounted on the rear. This configuration enabled Bandicoot to communicate with Joeys and localize their positions, regardless of whether they were in front of or behind the Deployer. (A small blind spot exists directly to either side of the Deployer where the Urban Robot's chassis blocks the ISIS signals.)

ISIS was used for directional line-of-sight communications, enabling the Deployer to identify the Joeys' positions and orientations, and allowing the Joeys to find the Deployer. The Swarm Radio was used for omni directional information transfer, allowing the Deployer to send general behavior commands to all Joeys and to receive sensor reports from each Joey.

A mast was designed and mounted on Bandicoot, as shown in Figure 7. In a retracted position, the robot retains invertibility and self-righting capability. Fully raised, the mast reaches 24 inches above ground. It is equipped with a pan/tilt platform and the following sensors:

- Panasonic color ccd camera (pan/tilt)
- IR and visible light pointer (pan/tilt)
- Directional antenna (pan only)
- RF radio antennae (stationary)



a.)

b.)

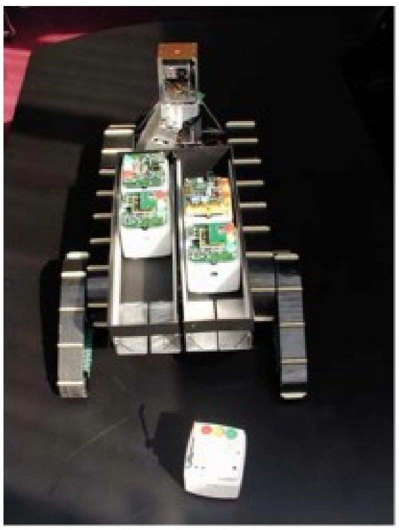
c.)

Figure 7: Deployer mast in a.) retracted, b.)extending, and c.) fully extended positions.

Deployer Outfitting - Wombat

The second Urban Robot, Wombat (Fig.8), was equipped with a single, rear-mounted ISIS transceiver and a Swarm Radio to communicate with all of the Joeys. In addition, Wombat was equipped with a passive linear deployment mechanism (PLDM) for the second-generation Joey.

The PLDM consists of a linear tray mounted on top of Wombat with a trap door mechanism that extends beyond the front of the Deployer. While being transported by the Deployer, the Joey rests at the rear end of the PLDM. During deployment, the Joey drives to the front of the mechanism, where it falls through the trap doors (Fig. 9). These doors are attached to the PLDM tray by elastic connectors, and the friction between the doors and the Joey are used to maintain the Joeys upright orientation upon deployment. After falling through the doors, the Joey drives away on its own.



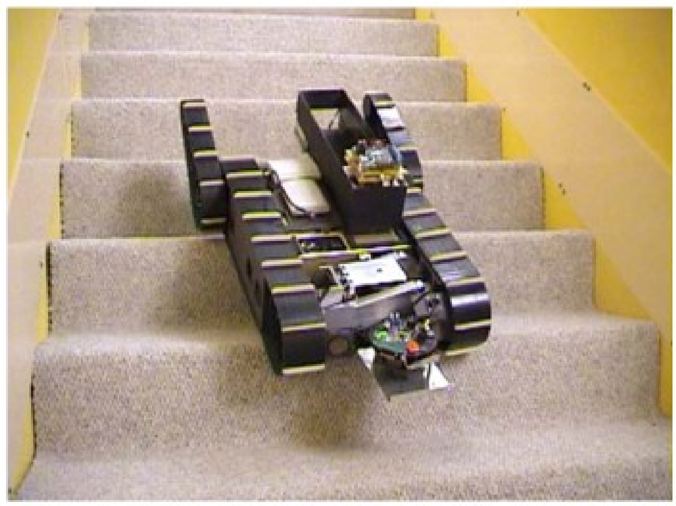


Figure 8: Wombat climbing stairs with PLDM and Joey.

The PLDM allows a Deployer to deliver Joeys to locations that they would otherwise be unable to reach. For example, a Deployer can climb a flight of stairs (Fig. 8) and then deploy a Joey to explore a different floor. Two PLDMs can be mounted on each Deployer, and three Joeys can be loaded in each PLDM. This enables each Deployer to carry up to six Joeys.

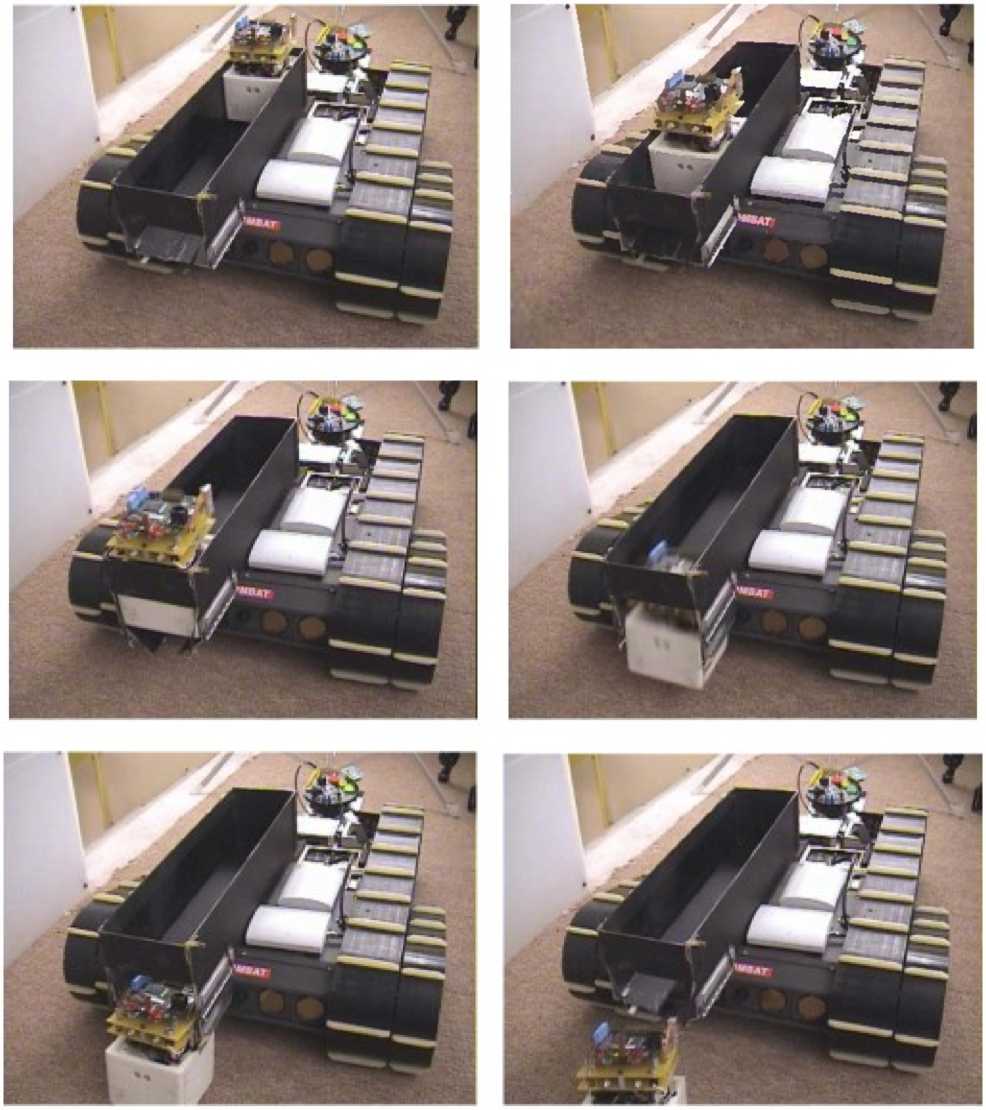


Figure 9: PLDM Joey deployment sequence. The Joey moves to the front of the chute (top), drops (middle), and moves away (bottom). A chute can hold 3 Joeys and 2 chutes can be placed on the Deployer (with antennas relocated).

Joey

The development of the Joey platform was done in two stages. First, a prototype that operates under RC control was designed, built, and evaluated (Figs. 10, 11, and 12). The final design was then modified to take into account evaluation results (Figs. 12 and 13). The resultant Joey robot now serves as the model for our 100+ robot swarm produced under the Software for Distributed Robotics (SDR) project. This is currently the largest swarm of robots in the world.

The system was designed specifically for low-cost mass production. The robot consists of a small number of parts that can be readily assembled.

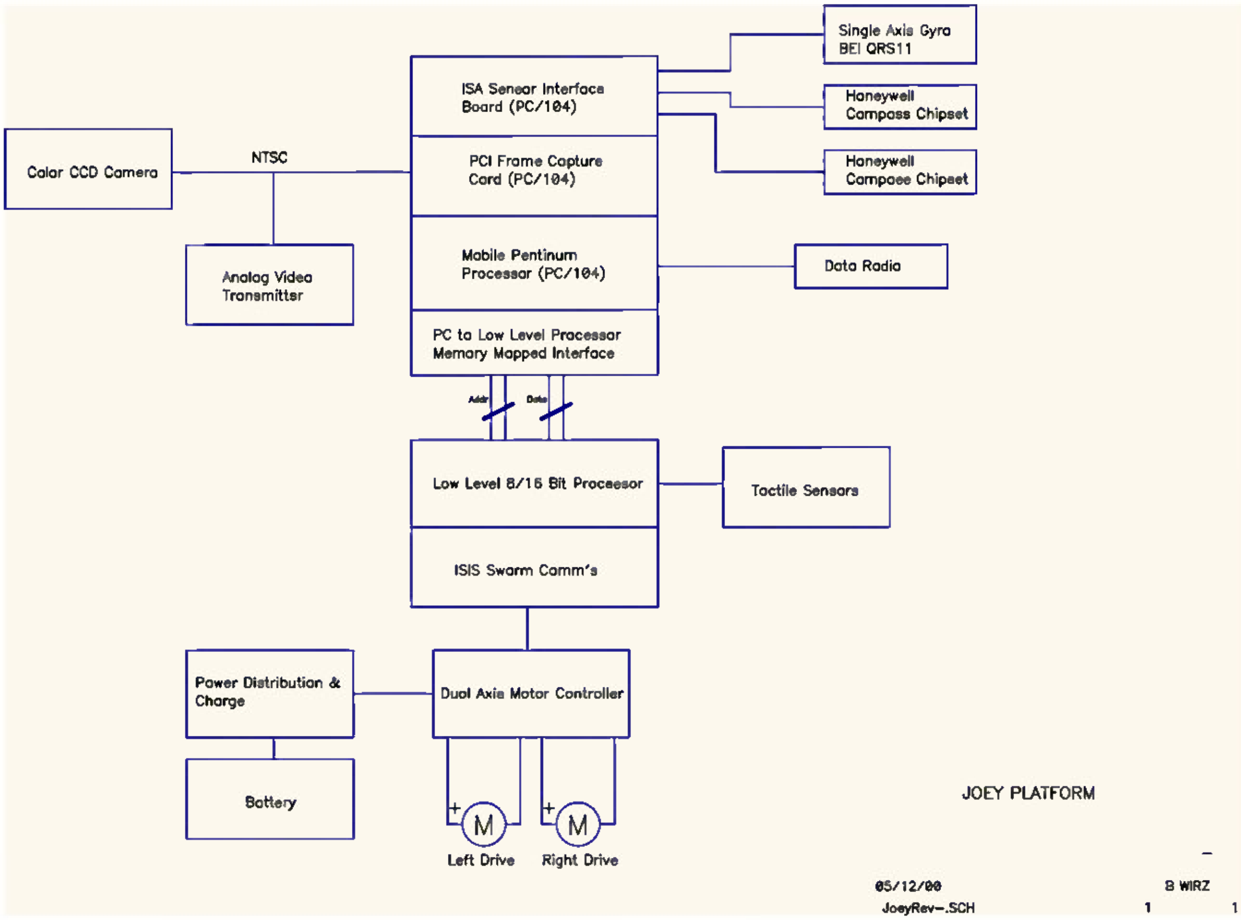


Figure 10: Electrical block diagram for the Joey Platform

Figure 11: The SDR Robot Swarm - 128 robots under assembly

Figure 12: COTS Swarmbot (left), Joey prototype (center), and final Swarmbot (right).

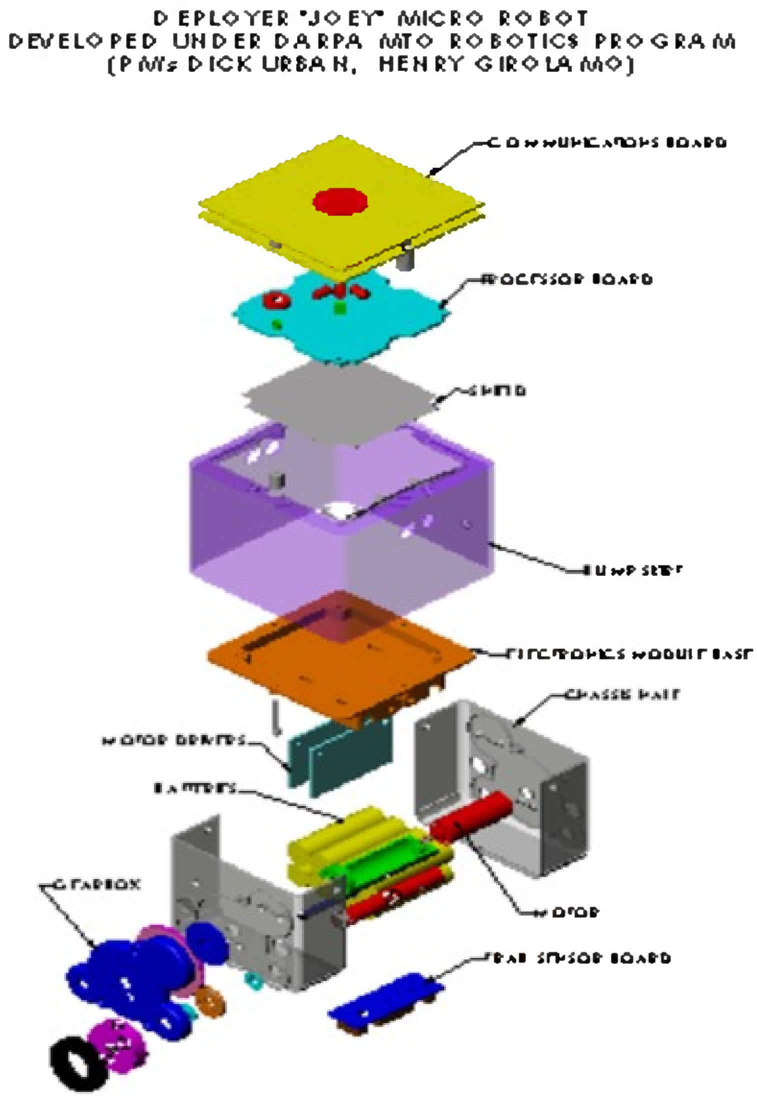


Figure 13: CAD schematic of the Joey robot, designed for low-cost production and assembly.

Joey Hardware

- Atmel AT91R40807 ARM Thumb running at 40mhz. 648kbytes RAM, 1-2 megabytes Flash EEPROM.
- Next-generation Xilinx device that will allow for more efficient bandwidth usage over the radio link
- ISIS 3.0 IR communication and obstacle detection system
- Monolithics TR1000 916Mhz 115kbps radio transceivers
- Bump sensors
- Small physical footprint
- 4 wheels, skid-steer
- Top mounted LED sensors for external tracking of Joey
- “Food” sensors (mission-specific sensors)
- Environmental sensor (water trail detector)

- 8 AA NiCd Batteries, 4+hours of run time
- Remote power-on, self recharge capability

3.5.2 C^2 Software Development

The Deployers and Joeys form an operational multirobot team that is capable of performing a variety of cooperative tasks. This team is called a Deployer/Swarm. IRobot's primary focus has been on the development of the Deployer/Swarm software necessary for autonomous and semi-autonomous behavior, including:

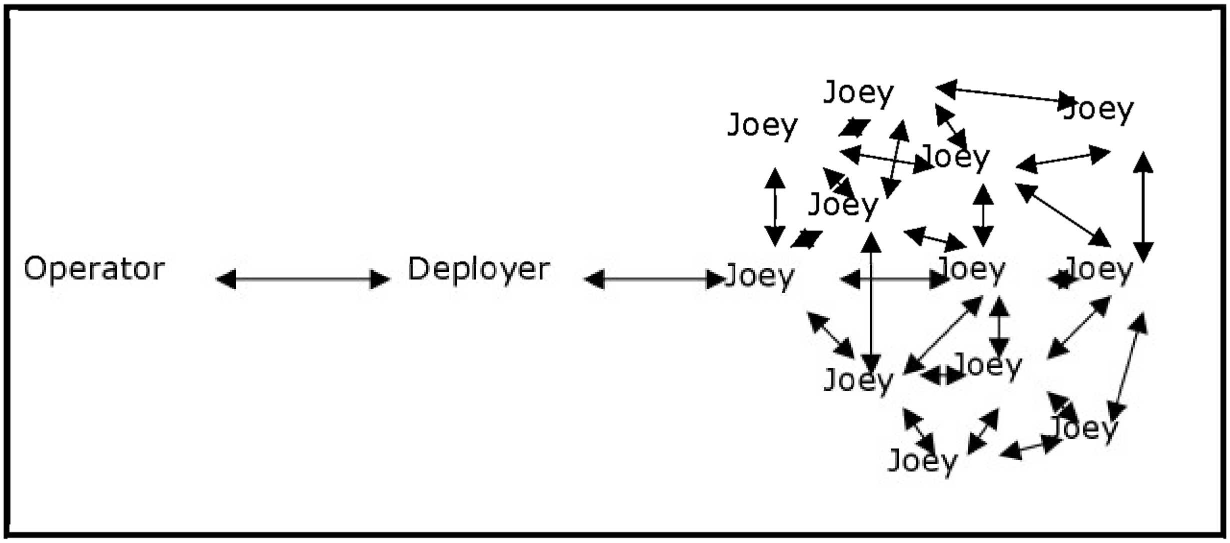
- **Coordinated motion**
  - Deployer leads the Swarm
  - Swarmbots move out of the way of the Deployer
- **Topological/metric mapping**
  - Deployer determines Swarmbot locations and uses this data to build a map containing topological and metric information.
- **Topological navigation**
  - Deployer plans and executes paths using the Swarmbots as beacons
- **Coordinated search**
  - Deployer and Swarm cooperate to search an unknown area
- **Grid-based mapping**
  - Swarmbots explore and the Deployer builds an occupancy grid map
- **Visually-guided motion**
  - Deployer uses vision to guide Swarmbots to specified location

In addition, iRobot developed a **unified map** display that can superimpose the maps constructed by the Deployer/Swarm on an existing floor plan. The operator can use this tool to register local grid maps with the global grid map.

In the remainder of this section we first list the requisite primitive behaviors and then describe each cooperative task in greater detail.

3.5.3 Underlying Software Primitives

Five classes of primitive behaviors were required as a base on which to build the heterogeneous C^2 behaviors outlined above: individual Joey behaviors, Joey-Joey interactions, Deployer behaviors, Deployer-Joey interactions and Operator to Deployer interaction. A sixth class, that of Deployer-Swarm interactions, is derived from combining Deployer-Joey and Joey-Joey interactions.



The libraries consist of the following primitives.

Individual Joey behaviors

1. Semi-random search
2. Waypoint following (dead reckoning)
3. Obstacle detect and avoid
4. Detect motion (ISIS)

Joey-Joey "swarm" interaction

(These swarm interaction primitives were built under the DARPA IPTO Software for Distributed Research program and leveraged here).

All of the Joey-Joey primitives depend on iRobot's proprietary ISIS infrared ranging and message passing system. Behaviors lower in the list are typically combinations of preceding behaviors.

1. Determine range and orientation of neighbor
2. Adopt and maintain set range and orientation to neighbor ("bonding")
3. Follow-the-leader
4. Form shapes (using multiple robots)
5. Establish communications gradient ("pheromone gradient")
6. Pass messages (data packet sent point-to-point or along pheromone gradient)
7. Path following (amidst other robots, along pheromone gradient)
8. Navigate thru pheromone gradient field
9. Goto goal (pheromone source)
10. Disperse (to minimum density that still preserves local communications)
11. Detect if on edge of swarm

Deployer behaviors

1. Waypoint following (dead reckoning – inertial navigation system, wheel encoders)
2. Obstacle detect and avoid (sonar, optic flow)

3. Retroverse (dead reckoning)
4. Detect communications signal drop-out and recover (via retroverse and possibly directional antenna)

Deployer-Joey interaction

1. Locate Joey (range and bearing) in Deployer coordinate frame (visual recognition of Joey top-mounted LEDs)
2. Set goto goal for Joeys (laser pointer generates "spot" and/or command dead reckoned offset)
3. Follow-me (home to LEDs)
4. Communications pipe for operator-Deployer-Joey

Operator-Deployer interaction

1. Communications pipe for operator-deployer-Joey
2. Supervised autonomy via Operator Control Unit
3. Superimpose Deployer and Swarm in operator selected coordinate frame (e.g., blueprint)

4 Results and Discussion

4.1 Launch Experiment

. The **Ballistic Launcher** was prototyped, mounted on the Deployer and tested. IRobot's complete set of goals were as follows:

- Round is a grenade-sized robot in a protective sabot: outer dim. 40mm x 110mm.
- Operating distance should cover a range of 7m to 15m (distance from Deployer to launch apogee (e.g., building window)). This is equivalent to a narrow alley or across a boulevard.
- Operating launch height should cover 1 to 3 stories.
- Launch energy should break glass.
- The launcher is radio controlled.
- The launcher should include a magazine to hold a number of robots.
- The launcher should be ejectable.

For the concept demonstration, the prototype was designed to test the first four goals to evaluate accuracy, energy, etc. Radio control, a magazine and an ejection device can be incorporated in a later design. We used a .22-caliber #4 nail gun cartridge for power. An advantage is that different explosive forces can be used to increase or decrease operating range as needed (#1 to #9 nail-gun cartridges are commercially available).

Two experiments with the ballistic launch prototype were conducted. In the first, a canvas-covered window was strung between two trees at a height of 5 meters. The Deployer was placed 5 meters away and launched a prototype "Scout" robot (40mm x 110mm, 210g, made of solid aluminum) 4 times. The Deployer was then moved back at 5-meter increments, and the 4-round launch was repeated, until the window was out of range (at 25 meters). Point of contact was recorded for each launch.

Results showed that the operating distance (to launch apogee) exceeded expectations and was good up to 20m. Repeatability was less than optimal.

We performed redesign/validation iterations on the launcher to improve accuracy and reliability. The launcher was then field tested on an abandoned building in Somerville, MA with four out of four perfect launches through second and third story glass windows (25' and 37' high, respectively). A video was made in which the test was incorporated into a simulated police action, courtesy of the Somerville MA Police Department. The video was shown at the Distributed Robotics Principal Investigators' meeting and copies distributed to DARPA and Soldier System Center sponsors.

Testing satisfied all four goals. While repeatability was excellent after tightening the camera mount, slippage is likely to occur in real application. The addition of a laser range finder would permit dynamic calibration and thus assure the operator of proper targeting. There were no problems shooting through panes of glass.

The launch appears to be very good for launching Micro Unattended Mobility Systems as well. In fact, this device could be used to launch MUMS rounds into wooden buildings, a material that the current MUMS program (DARPA ATO) has not been able to support.

4.2 Command and Control

Launching is only the beginning for a robot-deploying robot. Once the marsupial offspring are sprung, they need to coordinate with the Deployer robot and the operator to perform meaningful missions. The Deployer is equipped with better sensing, a longer-ranging communication device, greater computational power, and better mobility. Conversely, the relatively stupid Joeys can spread out to search areas in parallel, cluster on events of interest and serve as navigational beacons for the Deployer or operator. Together, they can efficiently and strategically search, map, guard and present a coherent view of a distributed region, with a minimal cognitive load on the operator.

To test desired functionality, we designed and built a system using the existing SDR Swarmbots and two Urban Robots, Bandicoot and Wombat, outfitted with special hardware, as described in Section 3. The Deployers and Joeys form an operational multirobot team that is capable of performing a variety of cooperative tasks, including:

- **Coordinated motion**
- **Topological/metric mapping**
- **Topological navigation**
- **Coordinated search**
- **Grid-based mapping**
- **Visually-guided motion**
- **Presentation of a unified map to operator**

4.2.1 Coordinated Motion

Follow Behavior

The first requirement for the Deployer/Swarm is the ability for the Deployer and the Swarm to move together in a coordinated fashion (Fig. 14). To maximize efficient use of human resources, a single operator should be able to direct the motion of the entire Deployer/Swarm. The operator does this by teleoperating the Deployer while all of the Swarmbots follow autonomously.

Figure 14: Swarmbots following Bandicoot.

The ISIS transmitters on the Deployer transmit an infrared pheromone signal that is received by the Swarmbots. When its **follow behavior** is active, each Swarmbot autonomously and independently homes in on this signal. In addition, each Swarmbot relays this signal to all of its neighbors. In this way, Swarmbots that do not have a direct line-of-sight to the Deployer can still follow the Swarm. The behavior that emerges from this interaction is similar to the behavior of ducklings following in a line behind a mother duck.

Flee Behavior

Since the Deployer can easily destroy a Swarmbot by crushing it under its treads, the Swarmbots need to move out of the way when they see the Deployer coming. Once again, the ISIS transmitters on the Deployer are used to transmit an infrared pheromone signal that the Swarmbots can sense. When a Swarmbot's **flee behavior** is active and the Swarmbot senses this signal, it turns around and runs away. The Swarmbots also relay this pheromone to their neighbors, causing their neighbors to run away even if they cannot directly see the Deployer. Using this behavior mode, the Deployer can safely move through the Swarm, with the Swarmbots dynamically clearing a path in front of the Deployer.

4.2.2 Topological/Metric Mapping and Navigation

Topological/Metric Mapping

One of the primary advantages of the Deployer/Swarm approach is the combination of the Swarm's ability to gather information from many places at once with the Deployer's computational power to process and integrate this information. This advantage is particularly apparent when the Swarm is used to explore unknown territory, and the Deployer uses the information from the Swarm to build maps that can be used for autonomous navigation.

Each Swarmbot uses its ISIS transceivers to maintain local awareness of the relative positions and orientations of its neighbors (Fig. 15). However, it does not have any global knowledge about its position in the world.

The Deployer collects the local information from each Swarmbot and assembles this information into a global map (Fig. 16) that contains the absolute position and orientation of each Swarmbot, along with the adjacency relationships between the Swarmbots.

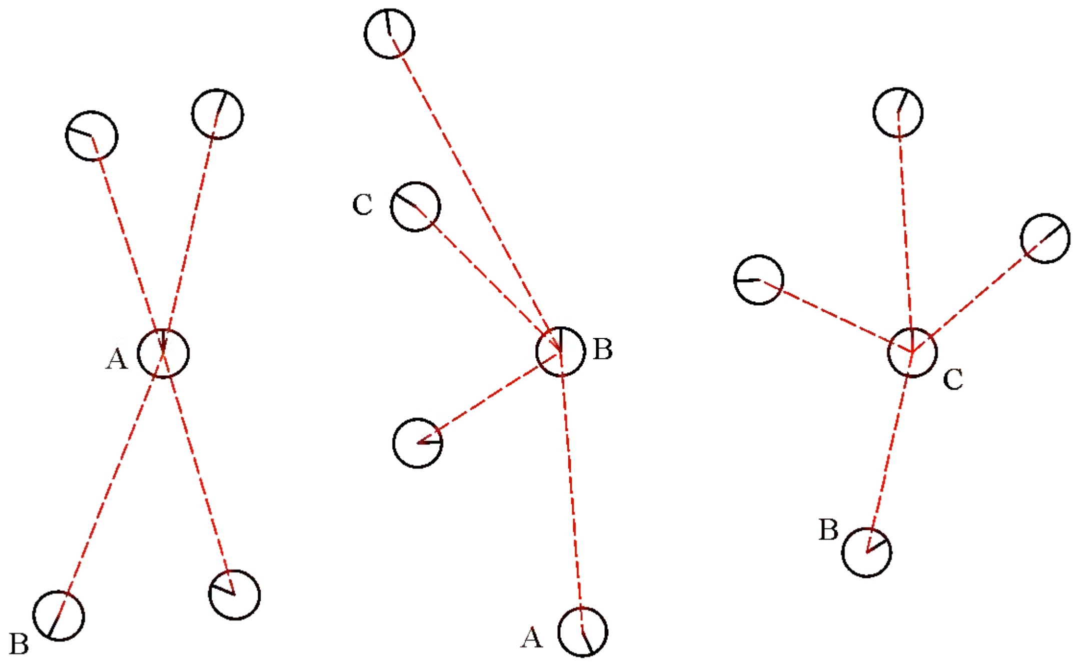


Figure 15: Local neighbor information for swarmbots A, B, and C.

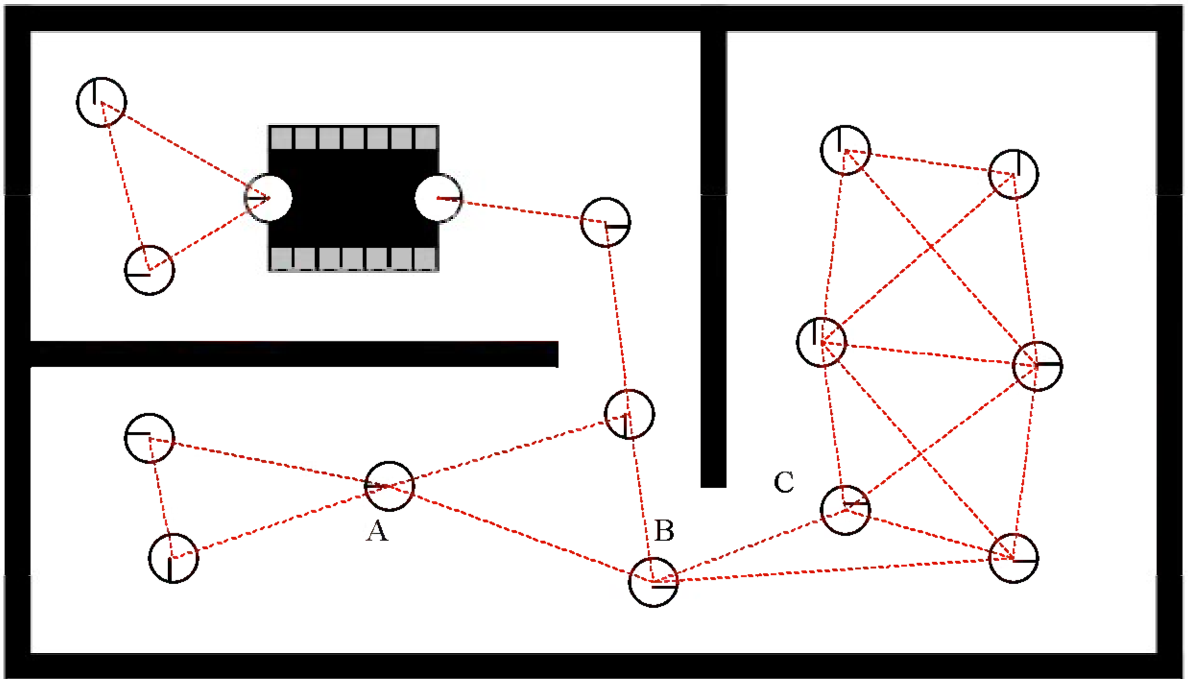


Figure 16: Topological/metric map constructed by Deployer.

This topological/metric map is constantly being updated to reflect the motion of the Swarmbots and the Deployer. This allows the Deployer to maintain an accurate estimate of all of the Swarmbot positions, even in a dynamic environment where all of the robots are moving.

Topological/Metric Navigation

Using the information in the topological/metric map, the Deployer can navigate to the location of any Swarmbot (Fig. 17). The Deployer finds a path to the destination consisting of a list of Swarmbot waypoints along with links containing the distance and relative bearing between adjacent waypoints.

The Deployer turns to align with the first Swarmbot on the path. Once aligned, the Deployer drives forward for a distance equal to the initial distance to that Swarmbot (as sensed by ISIS). As the Deployer moves forward, it transmits a pheromone via ISIS and tells all Swarmbots to flee. The Swarmbots move out of the way to allow the Deployer to reach its first waypoint.

After reaching this waypoint, the Deployer replans a path to the destination Swarmbot, using the newly updated information in the map. The Deployer then repeats this process with the next waypoint along the path, until it reaches its final destination.

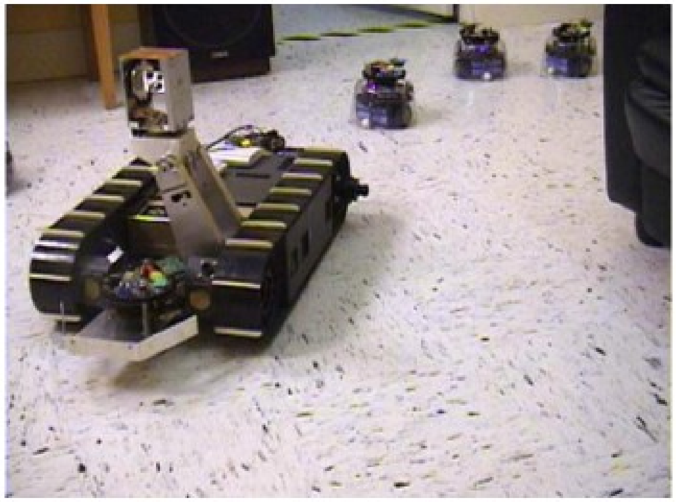


Figure 17: Bandicoot following Swarmbot path.

4.2.3 Coordinated Search

One of the most promising Deployer/Swarm applications involves searching for people in an indoor environment. For military reconnaissance, the Deployer/Swarm could search a building for enemy soldiers. For civilian search-and-rescue, the Deployer/Swarm could search for disaster victims. In either case, passive infrared motion detectors could be mounted on each Swarmbot, allowing it to detect the presence of moving humans at all times, and to detect stationary humans when the Swarmbot itself is in motion.

Once a human is found, the Deployer can navigate through the Swarm to deliver a payload to the human's location. For the combat application, this payload could be a teleoperated or autonomous weapons system. For the rescue application, this payload could include medical supplies and teleoperated medical assistance.

Since it can be difficult to obtain accurate absolute position information indoors (encoders slip, INS drifts, and GPS may be unavailable), we have developed a search algorithm that does not require precise metric localization. We call this algorithm **coordinated search**.

When the Deployer/Swarm moves into an unexplored area, the Swarmbots disperse from the Deployer using their **flee behavior** (Fig. 18). Once they reach a specified distance from the Deployer, the Deployer queries them for their neighbor information. The Deployer then integrates this information into a **topological map** that represents all of the Swarmbots' positions and adjacencies. If a Swarmbot has found a human, then the Deployer uses **topological navigation** to move through the Swarm to the human's location.

If no human has been found, the Deployer selects one of the Swarmbots as the **edge Swarmbot** and navigates to its position. The edge Swarmbot is the Swarmbot whose absolute position is the most distant from the centroid of all previously selected edge Swarmbot positions. Once the Deployer reaches the edge Swarmbot, the **follow behavior** is used to cause all Swarmbots to cluster on the Deployer's position. When all of the Swarmbots have arrived, the **flee behavior** is invoked again to cause the Swarmbots to disperse from the new Deployer location.

Since the edge Swarmbot is selected to be at the boundary of the previously mapped area, this sequence of actions will constantly lead the Deployer/Swarm toward unexplored territory. While some absolute position estimate is necessary (provided by the Deployer's encoders), the search algorithm degrades gracefully with position error. Increased position error means that the Deployer may not select the optimal edge Swarmbot, and exploration speed may be reduced. However, as long as the position estimate provides some useful information, the Deployer/Swarm will eventually explore the entire environment.

Figure 18: Swarmbots dispersing within a room via the flee behavior.

iRobot implemented and demonstrated the entire coordinated search algorithm. The Swarmbots are able to disperse through an indoor environment. The Deployer is able to select edge Swarmbots and navigate through the Swarm. The Swarmbots are able to cluster at the Deployer's new location, and disperse to explore new territory. The primary limitations on current performance are the Swarmbots' limited mobility (difficulty with uneven terrain, tendency to get caught on obstacles) and the lack of actual passive IR sensors for detecting humans. Both of these limitations could be addressed with improved Swarmbot hardware platforms, such as the six-wheeled Joey proposed by IS Robotics for the DARPA Tactical Mobile Robotics Throwbot program.

4.2.4 Grid-Based Mapping

iRobot also experimented with an alternative approach to mapping based on occupancy grids, where each grid cell represents the probability that the corresponding location is occupied by an obstacle. Topological/metric maps are best suited for autonomous navigation, since they provide a means for robust navigation in uncertain environments. Occupancy grid maps are best suited for teleoperation since they provide easy-to-understand graphical maps for human operators.

In order to build an occupancy grid map, the Deployer remains stationary while the Swarmbots wander randomly. The Deployer uses ISIS to keep track of the Swarmbots' positions. Since the space occupied by any Swarmbot is guaranteed to be obstacle-free, the corresponding cells in the grid are set to unoccupied. Over time, the Swarmbots wander through most of the open areas.

Initial experiments show that the general size and shape of the environment can be deduced from the resulting occupancy grid. However, the precise location of obstacles and other environment features can be difficult to determine. We believe that the performance of this mapping system can be improved through better understanding the characteristics of the ISIS sensor system.

4.2.5 Unified Map

In order to provide an easy-to-use interface for a human operator, we have developed the **unified map** tool. The unified map combines the information from multiple occupancy grid maps with an image representing the building floor plan (if available). As the Deployer/Swarm moves through the building, it constructs grid maps that are superimposed on the floor plan. This allows the user to see how the robots' perceptions of the actual environment match the a priori information about the building. For example, an operator attempting to guide the Deployer/Swarm toward a particular room within the building could use the floor plan for general guidance, while using the grid maps to steer around unexpected obstacles.

In addition, the unified map allows the user to register grid maps with each other, and with the underlying floor plan. Each of the grid maps can be translated and rotated independently, allowing the user to align features in the maps with features in the floor plan. This can be useful when correcting for odometry drift and other errors in position measurement.

4.2.6 Visually-Guided Motion

We developed the FlashFinder vision system to track and manipulate large numbers of small Joey robots by a single Deployer robot. No intelligence on the part of the Joey robots is assumed; they could be very simple remote control devices with no navigational sensors. Each Joey would have a flashing light of a unique color, flash period, and flash duty cycle. The Deployer can manipulate Joeys that are in its camera field of view, identifying each Joey and its location using the FlashFinder vision module.

To explain what the FlashFinder vision modules are and how they work (Fig. 19), the following sample application is discussed. This application drives a particular Joey to a specified pixel location in the image.

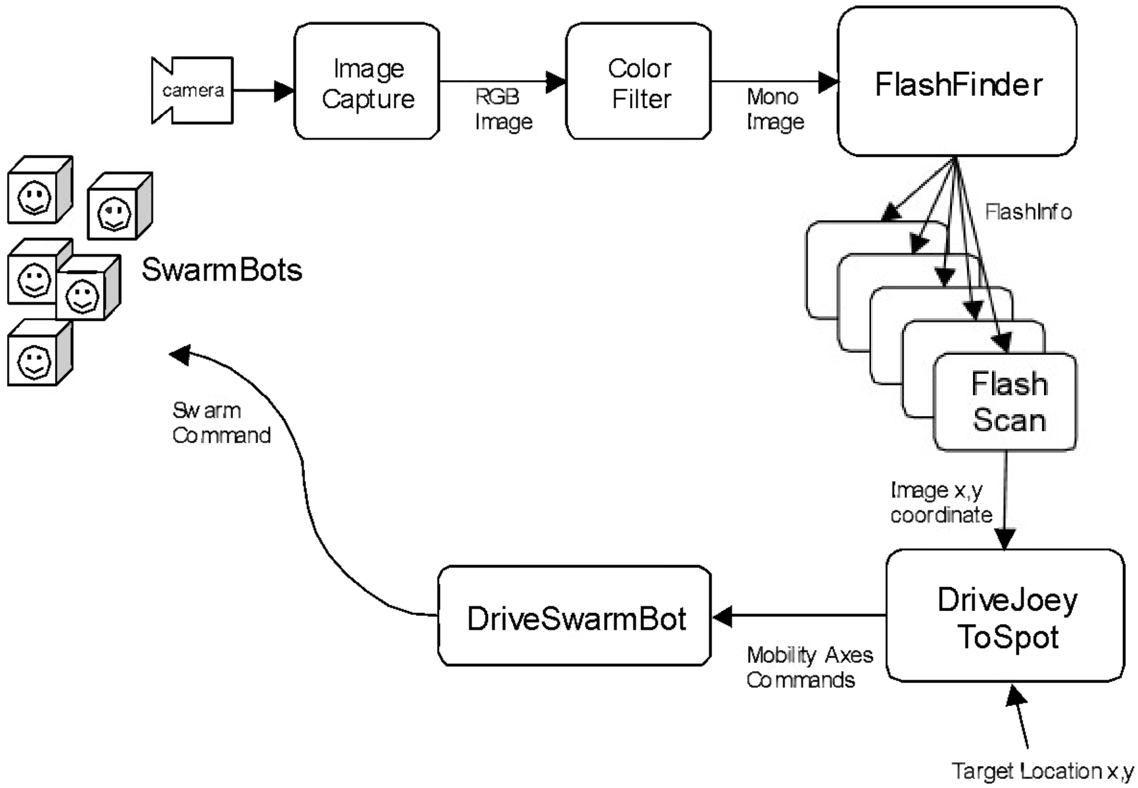


Figure 19: FlashFinder vision system.

The Image Capture module samples the video camera at periodic intervals, typically the faster the better. The images that are thus captured are filtered in software such that only a particular color of interest is allowed to pass into a monochrome image. For example, if all the identifying flashing LEDs are red, only the red portion of the captured images will be passed on.
The resulting periodic monochrome images received by the FlashFinder are scanned for periodic events that are greater than a certain threshold. Whenever a periodic event is found, its period and duty cycle are noted, as well as the jitter in the period of the periodic event. An adaptive threshold is applied on a pixel-by-pixel basis that allows for great sensitivity in some areas of the image and less sensitivity where the signal is very strong. Typically, flashing lights can be found using this method after a duration of three flash cycles, which is enough time to determine that the signal is indeed periodic. This method is also very good at rejecting spurious, non-periodic signals to minimize false positives. Since the FlashFilter module is looking for periodic events on a pixel-by-pixel basis, it works best when both the camera and the flashing lights are not moving.

The periodic event state map is passed on to the FlashScan modules. One such module is required to track each Joey of interest. In order to control multiple Joeys, each Joey must be flashing its LED at its own unique frequency. The FlashScan module scans the periodic event map looking for a particular flash frequency and duty cycle, within certain error bounds. When one or more pixels are found which meet the criteria, the module generates an output coordinate corresponding to the centroid of these pixels.

The observed Joey location is passed on to the "Drive Joey To Spot" module, which attempts to maneuver the Joey to a target location in the image by remotely controlling the Joey using the Deployer's Swarm Radio. This is done by an iterative process where the Joey is first located, then commanded to drive forward a distance. When the new location of the Joey is observed, the directional heading of that Joey can be estimated. The Joey is then commanded to turn towards the target location and the process repeats. The process needs to be iterative since no assumption is made about the Joeys ability to perform even simple navigation or odometry, so all drive and turn commands are performed open loop and uncalibrated or only roughly calibrated. The magnitude of future drive and turn commands is adjusted to try to get desired magnitudes, thus the module is automatically attempting to calibrate to the particular Joey.

5 Related Work

The related work in marsupial robotics is summarized in the following list of current and past activities. What is noteworthy is that nearly all efforts have been aimed solely at launching, usually under direct radio control by a human operator. Ours is the first program to address in any depth the issues of a pyramid of control from operator down to swarms of deployed robots.

Current Efforts:

1) University of Minnesota, Nikos Papanikolopoulos (DARPA MTO funded, DR program)
The UM team developed small 40mm cylinder robots, called Scouts and Rangers, that can roll and hop.
Launching: UM demonstrated packaging one of the robots in a sabot and launching it from an iRobot ATRV-Jr through a thin plane of glass at a distance of a few meters. Additional hardening is required for more powerful launching.
Control: The common control mechanism is direct radio control (RC) of each Scout by a single human operator. Robot to robot interaction exists in the form of a communication link between the ATRV-Jr and Scout over which a video stream can be passed from Scout to ATRV and processed on-board the ATRV.
Contact: http://www-users.cs.umn.edu/~npapas/
http://www.cs.umn.edu/Research/airvl/distributed

2) University of Florida, Robin Murphy: (DARPA ATO funded, TMR program)
The UF team carries 3 iRobot Urban Robots and an SAIC Su-Bot on 1 iRobot ATRV-Sr.
Launching: UF demonstrated a prototype launch by driving (under radio control) an Urban Robot off the back of the ATRV-Sr.
Control: The team has developed recognition algorithms for autonomous docking, based on color recognition invariant to light. Previous work included a launching an Inutken, a small tethered tracked vehicle from a child's modified Jeep.
Contact: http://www.csee.usf.edu/~murphy/

3) iRobot/Draper (DARPA ATO funded, TMR program)
An RC Urban Robot was modified to carry a ThrowBot-B.
Launching: The Throwbot-B was driven off the Urban Robot under radio control.

4) Foster Miller/SAIC (DARPA ATO funded, TMR program)

Launching: Radio control of SAIC Su-Bots on Foster Miller Lemmings. Ongoing status unknown.

5) Army Research Labs - Aberdeen (DARPA ATO, TMR program)
Launching: Phil Emmerman's group has demonstrated a launching concept by driving (under RC) an Urban Robot off the back of an ATRV-Sr.

Past Work:

A) 1996, Idaho National Labs/IS Robotics:
MACS, RACS and TRACS. RACS is the R-3 type robot developed at ISR and TRACS is the positioning beacon (also developed at ISR). MACS, a large K2A Cybermotion robot, carried RACS, which in turn carried TRACS.

B) 1994, ACAT project: BMDO/IS Robotics
ACAT and Grendel
A demo was performed by a 6-inch walking robot, Grendel, being deployed from a rocket propelled soft lander (the ACAT) after a short flight. This demonstration served as a genesis for NASA's fast and cheap space program, culminating, most recently, in the Pathfinder/Sojourner mission.

C) 1992, MIT AI Lab
Graduate student Cynthia Breazeal (nee Ferrell) deployed an Attila from a Russian rover in a California desert.

6 Conclusions

The integration of a more capable robot with a swarm of penetrating microbots has clear benefit. iRobot demonstrated in concept that such a system could be readily operated by a single operator for an efficient emergency response call.

In light of the Future Combat System, the Objective Force Warrior Program and Homeland Defense initiative, it is clear that intelligent control of large numbers of heterogeneous robots and sensors is critical to future success. These unmanned ground vehicles (UGVs), unmanned air vehicles (UAVs), unattended ground sensors (UGS), etc. must coordinate effectively and efficiently, present coherent information to the warfighter, and depend on minimal operator intervention. Each thrust of the work presented here applies equally.

Launch.
Initial strategic emplacement of microbots and microsensors bears significant ramifications on the speed to attain good surveillance and the quality of the data. Robots launched into 3-story buildings acquire information quickly and safely; signaling devices can be placed on building roves or hilltops to maintain line of sight communications; highly mobile systems can transport less agile systems to areas of otherwise unreachable terrain.

Command and Control

- **Maintenance**: maintaining the infrastructure to support the distributed front, including communications, error detection and recovery. A Deployer robot can patrol a perimeter, detect holes in distributed coverage, maintain contact with the warfighter for routine as well as dangerous missions.
- **Cooperation:** coordination among heterogeneous robots extends the capabilities of each type. Intelligent systems can identify key features in the terrain and direct less perceptive systems accordingly; numbers of small sensors can detect areas of interest and lead systems with specialized sensors or payloads to the hot zone.
- **Operator Control.** By providing a pipeline between Operator, Deployer and Swarm, the operator can occupy a safe, remote presence with minimized cognitive load.
- **Recovery**: intelligently collecting, filtering, and relaying data. Widely distributed data could appear as a mosaic of confusing snapshots, each taken from a different angle. The presence of a mobile, "centralized" robot permits the Deployer first, to have its attention focused in areas of key interest and, then, to amass a coherent presentation that is grounded in a single reference frame. In this way, parallel efforts such as distributed mapping can be assimilated on the spot, without waiting to recover the robots and unload their data.

7 Recommendations

The consideration of possible scenarios recommends several avenues of investigation. For example, a scenario that incorporates several of the launch concepts defined here might be as follows.

> "A drug cartel is believed to be holed up in a warehouse. It is unknown whether hostages have been taken. A sniper may be lodged on the roof to counter attempts by law enforcers to gain access.
>
> "From a secured location, a SWAT team member teleoperates a Deployer robot toward the warehouse. The officer activates a rocket-launched steerable Glider from the Deployers back over the building. As the SWAT member steers the glider, a camera mounted on the glider relays images to the operator's screen. Snipers are spotted.
>
> "The officer calls the Deployer back and pops off the glider launch rails, to replace them with a spinning "scatter" magazine. He loads Joey robots in some barrels, smoke and noise makers in others. He does the same for a second Deployer, including a homing LED beacon that will be shot on a near vertical trajectory (and so land near the Deployer). He teleoperates the second Deployer back to the warehouse entrance, with the other following close behind (autonomously). The first spins up its magazine and launches its payload, scattering distracters and robots seemingly randomly. The second Deployer is now teleoperated up the stairs and into the entrance under cover of noise and smoke. The first set of Joeys form a perimeter guard along the building entrance. Anyone leaving the building will be detected. The Deployer retreats but stays within communication range of at least one Joey.
>
> "Meanwhile, the second Deployer is inside the warehouse. It scatters its Joeys and its homing LED signal. It looks for motion; none is detected. The Deployer then pans the view sending the images back to the operator. The operator marks a doorway or likely hiding area. The Deployer tags the marked location with a laser pointer. Any Joeys in the vicinity of the

location see the light and move toward it, broadcasting their goal. The other Joeys hear the signal and follow their neighbors to the goal.

"The Joeys monitor communication signal back to the Deployer as they travel. If the signal drops out, the first to detect it retroverses to find it again and holds its position as a relay. The Deployer is now free to take cover in darkness, patrol the building, or return to the SWAT team to get another load of robots for a second launch. The Deployer can jettison its scatter magazine cartridge if needed for added mobility.

"Once past the goal, the Joeys disperse to minimum density while preserving communications amongst each other. All look for motion. If motion is detected, the Joey broadcast a warning. At irregular intervals the Deployer returns to its homing beacon and listens for warning broadcasts. If there is a warning, it moves toward the relay until it has direct communications with the Joey that is issuing the warning. Joey video is turned on and relayed to the teleoperator (or captured and archived) for review."

Once the robots developed under the Distributed Robotic program mature, new scenarios could incorporate and leverage their special capabilities. A few examples that use the Xerox Parc PolyBot or the University of Minnesota Scout:

1) PolyBot insertion into a vertical air duct, using the tether in collaboration with the Deployer to rappel down to a horizontal section that the PolyBot then explores.
2) Search and Rescue: the team of robots cooperatively searches for bodies in a room with the Deployer getting a quick scan by driving around and then the PolyBot filling in information for inaccessible areas.
3) The Deployer carrying a team of Scouts sneaks into a sewer system of a bunker. As the Deployer progresses up the main branch of the sewer, it releases a Scout into each branching tributary. After the Deployer can go no further, it retraces its path, collecting Scouts that have returned to their release points. Data that the Scouts have gathered is collected and processed for radio transmission when the Deployer emerges from the sewer system.
4) A Deployer quickly establishes that a room is unattended, and using a low power launcher, deploys Scout robots on desktops and shelves. The Scouts gather information about these areas, take pictures, and then roll back to the ground to be collected by the Deployer.

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